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Thermal Performance of Solar Cooker Based on Evacuated Tube Collector and PCM Storage Unit

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Abstract **- In this experimental set up, solar cooker with thermal storage unit was connected to evacuated tube collector through connecting pipes via a low flow rate pump. The design of solar cooker was such that the following fluid transfers its heat to PCM and cooking vessel simultaneously. Commercial grade acetanilide was used as latent heat storage material in the solar cooker. Cooking experiments were conducted during noon and evening with different loads and PCM storage processes were carried out simultaneously. The result include that cooking lunch for a family is possible simultaneously with heat storage along the day. Closing gate valves afterward allows cooking the dinner with the retained heat up to late evening. This expands the applicability of solar cooking and sustains the possibility of all the day around cooking using solar energy with a low inventory cost.**

Keywords: **Thermal Performance, Solar Cooker, Evaculated Tube, PCM Storage Unit**

I.INTRODUCTION

It is nearly 35 years since the first oil shock in 1973. Since then the words “energy crisis” and “energy security” continue to dominate the news. In spite of efforts to promote and develop renewable sources of energy and other new sources, fossil fuels (coal, oil & natural gas) continue to dominate the energy scene. While the need for alternative sources of energy is recognized, no set of alternatives has emerged which can take over the role played by fossil fuels. In India the energy crisis is a major problem. In spite of discoveries of oil and gas off the west coast, the import of crude oil continues to increase and the price paid for it now dominates all other expenditure. The need for developing energy alternatives is thus evident and considerable research and development work is already in progress to find some other alternative resources. Solar energy is one of them and it is non-polluting, free of cost and in abundance. In the recent years, storage of solar energy in day time and then using it in off-sun shine hours has become an important topic of research. A thermal storage system is the key to bridging the time gap between the thermal energy supply and the energy demand. It is classified as sensible, latent heat storage systems or the combination of these. The advantages of the latent heat system (LHS) in comparison with a sensible storage system are high heat storage density, small size of the system, and a narrow temperature change during charging and discharging processes. In the thermal energy storage system, energy is stored during the charging process while it is recovered during the discharging process. Solar energy can effectively be stored during the day using thermal storage units and thereafter it can be used later during off sunshine hours for cooking or other purposes. Among the different energy end uses, energy for cooking is one of the basic and dominant end uses in developing countries. Energy requirement for cooking accounts for 36% of total primary energy consumption in India. More than half of world populations rely on dung, wood, crop waste or coal to meet their most basic energy requirement. In India, particularly in rural area wood, agricultural wastes and animal dung cake are the main energy sources for cooking while in urban areas the main energy sources are kerosene and liquid petroleum gas (LPG).The cutting of trees for fire wood causes deforestation that leads to desertification and use of animal dung cakes pollute the environment. Also, the Continuous increase in fuel price indicates that there is an urgent need to utilize the various renewable energy sources in an effective way for cooking purpose. So, there is an urgent need to utilize the abundant and eco-friendly energy source such as solar energy for cooking purpose. Solar cooking has the following advantages:

1. Solar cooked food preserves most of the vitamins, minerals and antioxidants.
2. Solar cooked food is easily digestible. It gradually relieves stomach disorder, constipation, gastric trouble and acidity.
3. Solar cooking is absolutely free. Cost of solar cooker can be recovered through saving on conventional fuels.
4. In villages, women have to travel less often to forage for firewood, thus keeping them closer to home and safe as a result.
5. There are no chances of explosion or fire while using Solar Cooker. It is very dangerous for

household families with infants to use LPG, wood or microwave oven, as they are highly accident prone.
6. It helps in preserving our environment.
7. It is durable and simple to operate.

The most of the solar cookers fall within two main categories: Solar cooker without storage and solar cooker with storage.

A. Solar cooker without storage

Solar cookers without storage are classified into direct and indirect type solar cooker depending upon the heat transfer mechanism to the cooking pot. Direct type solar cookers use solar radiation directly in the cooking process while the indirect cooker use a heat transfer fluid to transfer the heat from the collector to the cooking unit. Commercially successful direct type cookers are box type and concentrating type cooker.

1. Box type cookers

Box type solar cooker is an insulated container with a multiple or single glass cover. This kind of cooker depends on the greenhouse effect in which the transparent glazing permits the passage of shorter wavelength solar radiation, but is opaque to most of the longer wavelength solar radiation coming from relatively low temperature heated objects. A double walled insulated box can also serve to hold the heat inside the cooker. Mirrors canbe used to reflect additional solar radiation into the cooking chamber. The speed of cooking depends upon the cooker design and thermal efficiency.
Box type solar cooker has the following advantages:

1. It can cook multiple pots simultaneously.
2. It can be made of any size to cook large quantities of food.
3. Multiple reflectors can be attached to enhance the performance of solar cooker.

The major limitation of box type solar cooker is that temperature beyond 150°C is difficult to achieve.

2. Concentrating type cookers

In the concentrating type solar cookers, the solar radiations are focused at a point or along a line by the reflectors. Concentrating type solar cooker is working on one or two axis tracking with a concentration ratio up to 50 and temperature up to 300°C which is suitable for cooking. Concentrating cookers utilize multifaceted mirrors, Fresnel lenses or parabolic concentrators to attain high temperatures.

Concentrator type solar cooker has the following advantages:

1. Temperature achieved at the bottom of the cooking vessel could be around 350°C to 400℃ which are sufficient for roasting, frying and boiling.
2. Food can be cooked quickly.

3.Indirect type cookers

Indirect type solar cooker, the pot is physically displaced from the collector and a heat transferring medium is required to convey the heat to the cooking pot. Solar cooker with flat plate collector, evacuated tube collector and concentrating type collector are commercially available cookers under this category. A limitation of solar cookers without storage is that cooking can only be done during sunshine hours. If solar cookers are provided with heat storing medium, then there is possibility of co cooking food during off sunshine hours.

B. Solar Cooker with Storage

Thermal energy storage is essential whenever there is a mismatch between the supply and consumption of energy. The solar cooker must contain a heat storage material to store the thermal energy in order to solve the problem of cooking outdoors and impossibility of cooking food due to frequent clouds in the day or during off sunshine hours. Thermal energy can be stored as a change in internal energy of material as sensible heat, latent heat and thermo chemical or combination of these. Solar cookers with storage are classified into sensible heat storage and latent heat storage type solar cooker depending upon the heat storage mechanism.

1. Sensible heat storage cookers

In sensible heat storage type solar cooker, thermal energy is stored by raising the temperature of solid or liquid. Sensible heat storage system utilizes the heat capacity and the change in temperature of the material during the process of charging and discharging. The amount of heat stored depends upon the specific heat of the medium, the temperature change and the amount of storage materials. The heat stored is given to the cooking food up to till the evening time. In this type of solar cooker the amount of heat stored is less.

2. Latent heat storage

Latent heat storage makes use of energy stored when a substance changes from one phase to another. The use of PCM for storing energy in the form of latent heat has been recognized as one of the areas to provide a compact and efficient storage system due to their high storage density and constant operating temperatures.

In latent heat storage type solar cooker, thermal energy is stored with rise in temperature coupled with change in phase. The heat stored is given to the cooking food up till the late night. So the solar cooker with latent heat storage could store more heat energy than the sensible heat storage. Advantages are :

1. Cooking can be done at night.
2. Cooking can continue if the sun goes behind clouds.
3. The cooker's temperature does not drop too much when cold food is added.

Solar intensity ranges from 700 to 900 W/m^2. Hence, solar cookers have good potential in India.

C.Phase Change Materials (PCM)

Phase change materials are substances which can absorb or release a large amount of heat at constant temperature. Heat is absorbed or released when the material changes from solid to liquid and vice versa. Phase change materials have high heat of fusion. When the material changes from solid to liquid phase a large amount of heat is absorbed and as the material is changed from liquid to solid, large amount of heat is released. Therefore phase change materials are termed as Latent Heat Storage Units. It is clear that there are countless types of phase change materials that are available at required temperature range. However, except for the melting point in the operating range, majority of phase change materials does not satisfy the criteria required for an adequate storage media. Some natural substances, such as salt hydrates, paraffin and paraffin waxes, fatty acids and other compounds which have high latent heat of fusion in the temperature range of 0℃ to 150℃ and these materials could be used for solar application. However, it may be asserted that most of the phase change materials today fall within three main categories: organic, Inorganic and eutectic.

1. Thermo- physical Properties of PCM

(a) Melting temperature of PCM in the desired operating temperature range.
(b) High latent heat of fusion per unit volume.
(c) High specific heat to provide for additional significant sensible heat storage.
(d) High thermal conductivity of both solid and liquid phase to assist the charging and discharging of energy of the storage system.
(e) High nucleation rate to avoid super cooling of the liquid phase.
(f) Non-corrosiveness to the construction materials.
(g) Chemical stability and cost effective.
(h) Nonflammable, nonpoisonous.

2. Application of PCM in thermal energy storage systems

(a) PCM is used to store the solar energy during the sunshine hours and this energy is utilized during off sunshine hours.
(b) PCM is used for heating domestic water.
(c) PCM is used for Medical application such as transportation of blood and hot cold therapies.
(d) PCM is used in solar power plants.
(e) PCM is used for Thermal protection of electronic devices.
(f) PCM is used for Thermal comfort in vehicles.
(g) PCM is used for heating the solar greenhouses.

The experimental comparison of different heat transfer fluids for thermal performance of solar cooker based on evacuated tube collector has been investigated for sun-shine and off sun-shine cooking. The transformer oil was used separately as heat transfer fluid to compare the thermal performance of solar cooker. The detail of experimental setup along with measuring devices and instruments are described in the dissertation. The experiments have been carried out in the July 2015.

II. OBJECTIVES OF THE PRESENT WORK

Some primary objectives of the present study are:

1. To make a comparison of thermal performance of solar cooker based on evacuated tube collector with different types of loads.
2. To study the effect of gate valve on discharging process of PCM.
3. To find out the sufficient solar thermal energy storage time of phase change material (Acetanilide) for late evening cooking.
4. To investigate the performance of solar cooker based on evacuated tube collectorwithout load and with load.

III. EXPERIMENTAL SETUP

The experiments were performed to investigate the thermal performance of solar cooker with thermal storage unit based on evacuated tube collector. The thermal performance of solar cooker was studied with a close loop pumping line containing transformer oil as a heat transfer fluids. Acetanilide is used as phase change material and it is filled in outer vessel surrounding the food container of the solar cooker. The photograph of evacuated tube collector with solar cooker is shown in Fig. 2. It consists of an evacuated tube collector, a solar cooker, gate valves, pump and connecting pipes. The experimental setup includes the following components:

1. Evacuated tube
2. Header
3. A/C motor pump
4. Solar cooker
5. Phase change material

6. Gate valve
7. Heat transfer fluid
8. Reflector

A. Evacuated tube collector

The evacuated tube collector consists of eleven evacuated tubes and a header (heat exchanger) as shown in Fig. 1. The length of tube is 1.5m and diameter of the outer glass tube and coated absorber tube are 0.047m and 0.037m respectively. Each evacuated tube consists of two glass tubes made from extremely strong borosilicate glass and vacuum ($P \leq 5x10^{-2}Pa$) is present between outer glass tube and absorber tube. The outer tube is transparent which allows light rays to pass through with minimal reflection. The inner tube is coated with a special selective coating of aluminum nitride (Al-N/Al) having excellent features i.e. solar radiation absorption and minimal reflection properties. The test sections of the evacuated tubes used in this system are shown in figures 2 (a) &2 (b). Each evacuated tube is filled with heat transfer fluid.

Fig. 1 Photograph of the experimental setup

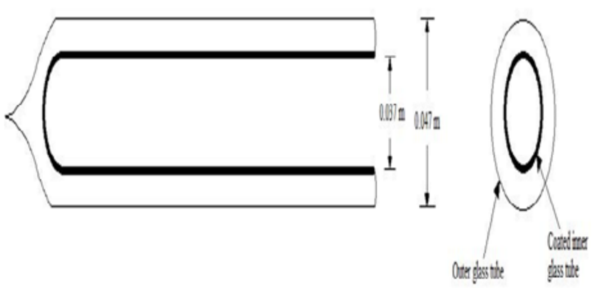

Fig 2 Schematic diagram of evacuated tube
(a) side view of evacuated tube
(b) front view of evacuated tube

B. Header

The test section of the header used in this system is shown in fig 3. It consists of a square pipe which is made up of stainless steel. In square pipe, eleven holes are created on the lateral surface of square pipe. Open end of the evacuated tubes are placed in these holes and the closed ends are supported by the frame.

On the outer surface of square pipe, an insulation of polyurethane is used to prevent the heat transfer from the header to the atmosphere. The outer casing of header is made with aluminum composite polymer sheet to hold the insulation. The header is filled with heat transfer fluid. One end of header is connected to the inlet of electric pump and other end is connected to outlet of the solar cooker.

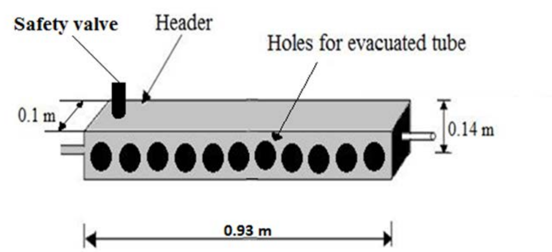

Fig. 3. Schematic diagram of header

C. A/C motor pump

In this experimental setup a copper pipe is coiled around the copper cooking vessel so there is no natural circulation of HTF inside the coil to resolve this problem a pump is used which continuously circulate HTF from the header to the cooking vessel so that heat is transfer from ETC to the PCM. This pump have very low flow rate so that more heat is transfer from HTF to PCM. The specification of the pump is following:-

TABLE 1 SPECIFICATION OF THE PUMP

Parameter	Value
Power	40W
Ampere	0.18
Max Flow	18 LPM
Max Head	3.5 meter

D.Solar Cooker

Solar Cooker as shown in figures 5 (a) and 5 (b) is made up of two hollow concentric cylindrical vessels.

The outer vessel having diameter 0.21mis of aluminium and filled with 3kg of commercial grade Acetanilide (phase change material). The allowance is given in the outer vessel for volumetric expansion of PCM. The inner vessel having diameter 0.11m made of copper is used for cooking and a lid is provided over the same. Two safety valves for PCM unit are provided on the top surface of solar cooker. The photograph of solar cooker is shown in Fig. 6.

Fig. 4. *Solar Cooker*

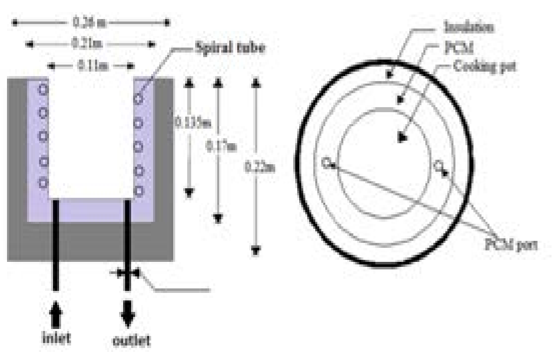

Fig. 5 Schematic diagram of solar cooker (a) side view of cooker (b) top view of cooker

E.Phase Change Material

A phase change material is a substance with high heat of fusion which is capable of storing and releasing large amount of energy. Heat is absorbed or released when the material changes from solid to liquid and vice versa. The selection of phase change material depends upon its properties such as melting temperature, latent heat of fusion, toxicity etc. In this solar cooker, the phase change material used was commercial grade acetanilide with its thermo physical properties given in Table 2.

Fig. 6 . Photograph of the top view of solar cooker

TABLE 2 THERMO PHYSICAL PROPERTIES OF COMMERCIAL GRADE ACETANILIDE

Properties	Values
Melting temperature of acetanilide (commercial grade)	118.9℃
Latent heat of fusion of acetanilide (commercial grade)	222 kJ/kg
Specific heat of acetanilide	2 kJ/kg℃
Density of acetanilide	1210 kg/m^3

F.Reflector

Reflector is used beneath the evacuated tubes to reflect the sunlight on the evacuated tubes. The dimensions of reflector are 1.39m x 0.90m. It is basically zinc coated galvanized aluminium sheet with a reflectivity of 86% at clean surface. The coating of zinc provides good reflectivity so that it can easily reflect the incident solar radiations on evacuated tubes. By using reflector, the temperature of heat transfer fluid and PCM is increased.

G. Gate Valve

The two gate valves are provided at the inlet and exit of the solar cooker. They are used to disconnect the solar cooker from the evacuated tube collector during discharging of PCM. The gate valves are closed in the evening time at 15:00hr. Photographic view of the gate valve is shown in Fig. 8.

Fig. 7 Photograph of the gate valve

H. Heat transfer fluid

In the experimental setup, transformer oil is used separately as heat transfer fluids. Heat transfer fluid is filled in the whole circuit including evacuated tubes, connecting pipes and copper coil heat exchanger. The heat transfer fluid circulates with help of pump to transfer the heat from the evacuated tube to the cooking vessel.

IV. MEASURING DEVICE AND INSTRUMENTS

Different parameters measured are:

1. Heat transfer fluid temperature, PCM temperature and food temperature
2. Ambient temperature
3. Solar radiation intensity

These parameters are measured by following devices:

A. RTD PT100 Thermocouples

RTD PT100 thermocouples are used to measure the temperature of heat transfer fluid, PCM temperature and food temperatures. The thermocouples are connected with a digital temperature indicator that gives the temperature with a resolution of 0.1℃. A photograph of RTD PT100 sensor with digital temperature indicator is shown in Fig 9.

A RTD (Resistance temperature detector) is basically a temperature sensitive resistor. It is a positive temperature coefficient device which means that the resistance increases with temperature. The resistive property of the metal is called its resistivity.

The criterion for selecting a material to make a RTD is

1. The material must be malleable so that it can be formed into small wires.
2. It must have a repeatable and stable slope or curve.
3. The material should also be resistant to corrosion.
4. The material should be of low cost.

Fig. 8 Digital temperature indicator with RTD PT100 Sensor

RTD PT100 thermocouple which is used in the experimental analysis works in the range of 0℃ to 200℃. The platinum RTD has the best accuracy and stability among the common RTD materials. Platinum has a very high resistivity, which means that only a small quantity of platinum is required to fabricate a sensor and making platinum cost competitive with other RTD materials. Platinum is the only RTD commonly availablewith a thin film element style. Copper, nickel and nickel iron are also commonly used RTD materials. They are mostly used in lower cost noncritical applications.

B.Pyrometer

The pyrometer is used for the measurement of global solar radiation received on a horizontal surface. The Fig. 10 shows the photograph of pyrometer. It has sensitive surface which is exposed to total (beam + diffuse + reflected from earth and surrounding) radiations. The sensitive surface consists of a circular, blackened (hot-junction) multi-junctions thermocouple whose cold junctions are electrically insulated from the basement.

The temperature difference between hot and cold junctions is a function of the radiation falling on the surface. The sensitive surface is covered by two concentric hemispherical glass domes to shield it from wind and rain. This also reduces the convention current. Pyrometer when provided with an occulting disc, measures the diffuse radiation. This disc or band blocks the beam radiation from the surface. It may be noted that the pyrometers are calibrated so as to measure the solar radiation on the horizontal surface. Therefore when tilted, the change in free convection regimes within the glass dome may introduce an error in measurement.

Fig .9 Pyranometer with digital display unit

In most pyranometer, the solar radiation is allowed to fall on a black surface to which the hot junctions of a thermopile are attached. The cold junctions of the thermopile are located in such a way that they do not receive the radiation. As a result an e.m.f. is generated, which is proportional to solar radiation.

V. SYSTEM OPERATION

The experimental setup consists of eleven evacuated tubes, a header, connecting pipes, pump and a solar cooker. The inlet and outlet of the solar cooker are connected with header through connecting pipes. The inlet is connected to header via a pump whereas outlet is directly connected to header.

Two gate valves are used at the inlet and outlet of solar cooker respectively which are kept open during PCM charging process. The schematic diagram of the experimental setup is shown in Fig.11.During sunshine hours solar radiations are absorbed by the evacuated tube collector and also a reflector is used beneath the evacuated tube which reflects solar radiation on the bottom surface of evacuated tubes. The heat absorbed by the evacuated tubes is transferred to the heat transfer fluid which is filled in it.

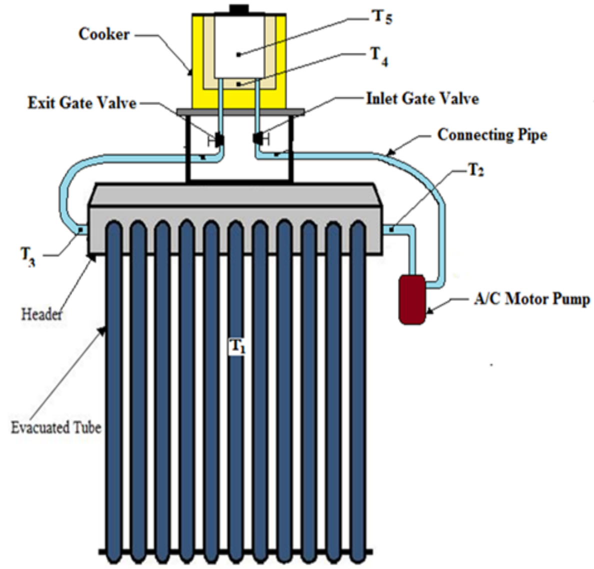

Fig. 10 Schematic diagram of experimental setup with solar cooker and PCM storage unit

The hot heat transfer fluid flows through ETC and get filled in header. A pump (40W) circulates the heated transformer oil (HTF) from the ETC through the insulated pipes to the PCM storage unit using a copper tubing (diameter21.6mm) heat exchanger that wraps around the cooking unit in a closed loop as shown in Fig. 1. A photograph of the cooper tubing heat exchanger is shown in Fig. 3.

A pump with sufficient power was selected because of the large frictional resistance in the solar collector and pipe circuit.During this process heat transfer fluid transfers heat to the thermal storage unit. The thermal storage unit stores and transfer heat to the cooking vessel during night time.

During the day time, the heat transfer is an instant process, as heat is transferred to cooking pot as well as get stored in PCM storage unit. During off sunshine hours, stored energy of PCM is utilized to cook food in late evening. During the discharging process of PCM, two separate cases are considered, first when both the valves are open and second when both the valves are closed.Five thermocouples were used for measuring the ambient temperature, temperature at header exit, temperature at cooker inlet, temperature at cooker exit, temperature at header inlet, temperature of PCM and temperature of cooking load.

The experiments were carried out mostly in clear sky days in the month of July 2015.Three cases are considered to investigate the thermal performance of solar cooker. In first case, 700ml of water was used as cooking load. In second case, pulse and rice were used as cooking load separately.

The different cases considered are given below:

1. Evacuated tube solar cooker with loading (700ml water) and transformer oil as heat transfer fluid

    a) Pump ON and both gate valves open during the discharging of PCM.

    b) Pump OFF and both gate valves close during the discharging of PCM.

2. Evacuated tube solar cooker with transformer oil as heat transfer fluid and both gate valves closed during discharge of PCM.

    (a) With cooking load (200gm pulse + 700 ml water) pump OFF.

    (b) With cooking load (200gm rice+700ml water) pump OFF.

VI. RESULTS AND DISCUSSION

The main objective of this experimental setup was to compare the thermal performance of solar cooker based on evacuated tube collector with different heat transfer fluid and effect of gate valves on the discharging process of PCM.

The experiments were conducted during the month of July, 2015. In most of the days, the ambient temperature was in the range of 23°C to 34°C. Every day, solar collector was exposed to solar radiation at 8:30hr and readings were taken from 09:00hr at an every interval of 30minutes. The evacuated tube collector was faced towards the south.

A.Evacuated tube solar cooker with transformer oil as heat transfer fluid

1. Day 1: Both gate valves open during discharging of PCM

Table 3 shows the Data of ambient temperature, HTF temperatures, and PCM temperatures with time and solar intensity in case of both gate valves open during discharging of PCM and transformer oil as heat transfer fluid

TABLE 3 DATA OF AMBIENT TEMPERATURE, HTF TEMPERATURES, AND PCM TEMPERATURES WITH TIME AND SOLAR INTENSITY IN CASE OF BOTH GATE VALVES OPEN DURING DISCHARGING OF PCM AND TRANSFORMER OIL AS HEAT TRANSFER FLUID

Time (hrs.)	Solar Intensity(W/m²)	T_{amb} (°C)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)
9:00	382	25	44.9	24.5	24.2	23	20.6
9:30	467	26	65.1	29.8	26.2	24.1	22.7
10:00	552	27	85.6	34.5	33.7	25.9	25.5
10:30	642	28	97.1	45.6	43.7	26.4	27.2
11:00	714	28.5	104.2	56.4	52.3	33.2	36.8
11:30	750	29.5	108.4	91.8	82.1	71.3	71
12:00	770	31.5	113.7	102.2	94.2	80.8	81.2
12:30	750	32	118.9	103.1	100.2	91.9	90.6
13:00	737	32.5	120.9	107.6	104.4	96.1	95.7
13:30	693	33	116.3	110.9	108.8	103.7	101.5
14:00	607	34	115.2	111.1	110.2	106.3	104.1
14:30	520	33	112.5	109.8	107.3	105.6	108.9
15:00	415	32	110.3	105.7	97.5	101	107.8
15:30	323	31.5	101.6	97.8	83.5	97.9	103.4
16:00	205	30	99.6	89.1	68.2	93.9	97.9
16:30	101	30	100.8	73.7	56.2	75.1	92.1
17:00	34	28.5	96.7	60.2	45.4	71.9	84.8

On July 23, the experiment was performed with thermal oil as HTF with cooking load of 700ml of water and both gate valves were kept open throughout the day. During the day, the maximum intensity was 770W/m^2 and the range of ambient temperature was 25.0°C to 34.0°C. The maximum temperature inside evacuated tube was 120.9°C at 13:00hr while at the same time temperatures at header exit, header inlet, PCM, cooking port were 107.6°C, 104.4°C, 96.1°C and 95.7°C respectively.

The maximum temperature attained by HTF inside cooker and PCM were 108.9°C and 106.3°C respectively as shown in Fig. 12.In the morning session, cooking load was loaded at 10:00hr. Initially, the temperature of cooking load was nearly ambient temperature. As the solar intensity increases, the temperature of heat transfer fluid (transformer oil) rises and heat energy is transferred to the cooking vessel through PCM. At the same time, some part of the solar energy is stored by PCM.

The maximum temperature of cooking load was 108.9°C in 14:30hr.In the evening session, the cooking load was placed in the cooker at 16:00hr. In the beginning, the temperature of cooking load was nearly ambient temperature. As the solar intensity decreases, the temperature of heat transfer fluid (transformer oil) decreases. During this time PCM transfer its stored energy to the cooking vessel. The cooking load attained maximum temperature of 84.8°C at 17:00hr.

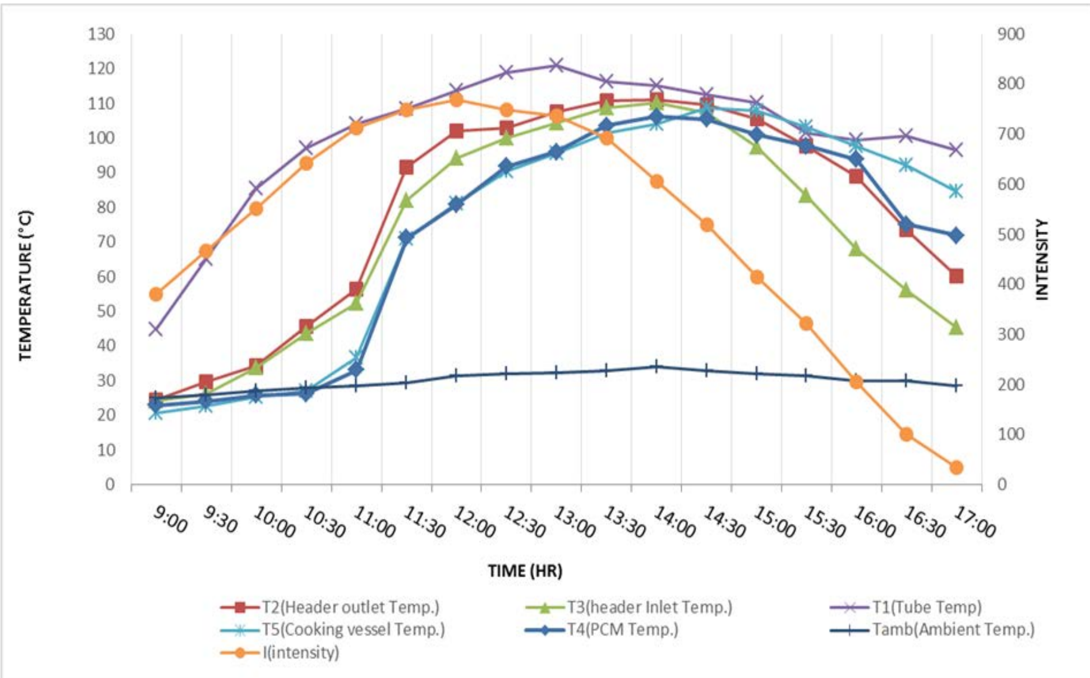

Fig.11 Variation of temperatures and solar intensity with time in case of both valve open and transformer oil as heat transfer fluid on July 23, 2015

2. *Day 2: Both gate valves close during discharging of PCM*

On July 24, the solar cooker was loaded with same cooking load of 700ml of water and both gate valves were kept closed during discharging of PCM. Fig. 13 shows that the maximum intensity during the day was 728W/m^2 and the range of ambient temperature was 23.5°C to 31.0°C. The maximum temperature inside evacuated tube was 128.3°C at 13:00hr and at the same time temperatures at header exit, header inlet, PCM, cooking port were 107.8°C, 104.3°C, 98.7°C and 101.4°C respectively.

The maximum temperature attained by HTF inside cooker and PCM were 109.2°C and 101.9°C respectively.In morning session, cooking load was placed in the cooker at 10:00hr. Initially, the temperature of cooking load was nearly ambient temperature. As the solar intensity increases, the temperature of heat transfer fluid (transformer oil) rises and heat energy is transferred to the cooking vessel through PCM. At the same time, some part of the solar energy is stored by PCM. The maximum temperature attained by cooking load was 109.2°C in 14:30hr.In the evening session, the gate valves were closed at 15:00hr and pump was OFF. The cooker was loaded at 16:00hr. In the beginning, the temperature of cooking load was nearly ambient temperature. As the solar intensity decreases, the temperature of heat transfer fluid (transformer oil) decreases. During this time PCM transfer its stored energy to the cooking vessel. The maximum temperature attained by cooking load was 91.7°C at 17:00hr.

TABLE 4 DATA OF AMBIENT TEMPERATURE, HTF TEMPERATURES, PCM TEMPERATURES WITH TIME AND SOLAR INTENSITY IN CASE OF BOTH GATE VALVES CLOSED DURING DISCHARGING OF PCM AND TRANSFORMER OIL AS HEAT TRANSFER FLUID

Time(hrs.)	SolarIntensity(W/m2)	T_{amb} (°C)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)
9:00	364	23.5	46.2	24	23.4	21	20.6
9:30	452	24.5	63	28.1	27.8	24.8	22.6
10:00	535	26	82.5	32.9	28.8	27.2	25
10:30	618	27	98.7	37.1	32.4	29.7	27.7
11:00	667	28.5	110.2	40.5	35.4	30.8	30
11:30	715	29	114.4	76.1	74.1	69.9	67.8
12:00	719	29.5	118	88	84.9	78.2	82.4
12:30	728	30	125	102.7	94.8	91	88.7
13:00	709	31	128.3	107.8	104.3	98.7	101.4
13:30	675	30.5	127.8	113	109.2	101.9	106.2
14:00	579	31	114	114	111.7	101.6	108
14:30	548	30.5	110	111.2	107	101.3	109.2
15:00	454	29.5	108.9	105.8	99.4	95.1	108.9
15:30	333	28	100.4	86.6	78.6	84.2	103.8
16:00	248	27.5	97.2	70.4	63.6	73	98.2
16:30	98	27	95.8	54.6	54.3	60	96.6
17:00	34	27	94.6	49.1	44.5	55.3	91.7

B. Solar cooker with transformer oil as heat transfer fluid and both valves closed

Out of the different case which are studied till now in this section, it can be observed that the temperatures of HTF and PCM are high in case of transformer oil as heat transfer fluid and both valves closed. Also in this case, cooking load has temperature nearly 80°C up to 17:00hr which is higher among all cases and shows the possibility of cooking in evening session.

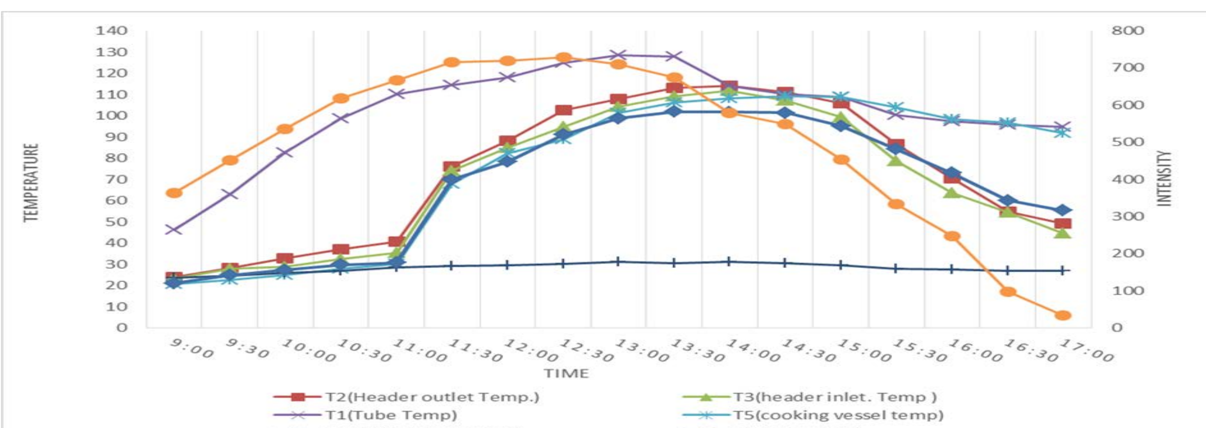

Fig.12 Variation of temperatures and solar intensity with time in case of both valves closed and transformer oil as heat transfer fluid on July 24, 2015

3. *Day 3: With cooking load (200g pulse + 700ml water)*

TABLE 5 DATA OF AMBIENT TEMPERATURE, HTF TEMPERATURES, PCM TEMPERATURES WITH TIME AND SOLAR INTENSITY IN CASE OF SOLAR COOKER WITH 200G PULSE AS COOKING LOAD AND TRANSFORMER OIL AS HEAT TRANSFER FLUID WITH BOTH GATE VALVES CLOSED AND PUMP WAS OFF

Time(hrs.)	SolarIntensity(W/m2)	T_{amb} (°C)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)
9:00	444	23	43.8	24.5	23.1	22.1	
9:30	519	23.5	62.2	29.3	25.1	29	
10:00	625	25.5	81.4	33.7	28.6	33.4	25.5
10:30	709	26.5	96.9	38.7	31.2	37.6	27.8
11:00	802	28	114.7	47.4	43.5	41.6	37.2
11:30	821	29.5	128.9	81.8	78.1	71.3	67.3
12:00	863	30	131.3	93.8	89.7	82.6	76.1
12:30	837	30.5	135.6	109.9	105.1	94.8	83.4
13:00	845	30.5	141.2	117.1	111.1	103.2	89.7
13:30	798	31	124.1	115.8	113.4	105.9	
14:00	700	31	117	109.4	108.2	98.7	
14:30	673	31.5	107.6	105.8	105.6	97.1	
15:00	476	32	103.7	105.2	103.8	91.4	35.4
15:30	411	31.5	99.2	97.9	61.3	87.4	82.6
16:00	289	30	97	83	47.2	80.8	76.3
16:30	190	30	93.2	65.8	35.6	75.6	73.1
17:00	56	29	89.4	54.6	32.3	72.4	70

On July 25, the experiment was conducted with pulse as cooking load. Fig 14 shows that the maximum intensity during the day was 863W/m^2 and ambient temperature was in the range of 23.0°C to31.5°C. The maximum temperature inside evacuated tube was 141.2°C at 13:00hr while at the same time temperatures at header exit, header inlet, PCM, cooking port were 117.1°C, 111.1°C, 103.2°C and 89.7°C respectively. The maximum temperature attained by HTF inside cooker and PCM were 117.1°C and 105.9°C respectivel In the morning session of cooking, cooking load was placed in the cooker at 10:00hr. Initially, the temperature of cooking load was nearly ambient temperature. As the solar intensity increases, the temperature of heat transfer fluid (transformer oil) rises and heat energy is transferred to the cooking vessel through PCM. At the same time, some part of the solar energy is stored by PCM. The maximum heat stored by PCM during charging process was 461.5kJ. The food was found to be well cooked at 13:00hr and maximum temperature of food was 89.7°C. In the evening session, the gate valves were closed at 15:00hr and food was placed in the cooker at15:00hr and pump was OFF. In the beginning, the temperature of cooking load was nearly ambient temperature. As the solar intensity decreases, the temperature of heat transfer fluid (transformer oil) decreases. During this time PCM transfer its stored energy to the cooking vessel. The food was well cooked at 17:45hr and maximum temperature of food was 76.3°C at 16:00hr.

4. *Day 4: With cooking load (300g pulse + 700ml water)*

On July 26, the experiment was performed with pulse as cooking load. During the day,maximum intensity was 892W/m^2 and ambient temperature was in the range of 23.0°C to 31.5°C table 6 shows data of ambient temperature, htf temperatures, pcm temperatures with time and solar intensity in case of solar cooker with 300g pulse as cooking load and transformer oil as heat transfer fluid with both gate valves closed and pump was off

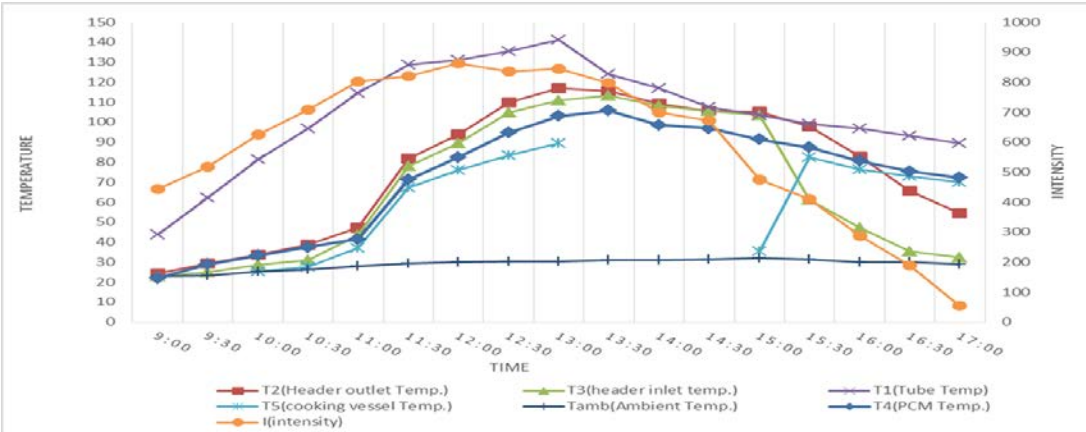

Fig.13 Variation of temperatures and solar intensity with time in case of both valves closed and oil as heat transfer fluid on July 25, 2015

TABLE 6 DATA OF AMBIENT TEMPERATURE, HTF TEMPERATURES, PCM TEMPERATURES WITH TIME AND SOLAR INTENSITY IN CASE OF SOLAR COOKER WITH 300G PULSE AS COOKING LOAD AND TRANSFORMER OIL AS HEAT TRANSFER FLUID WITH BOTH GATE VALVES CLOSED AND PUMP WAS OFF

Time(hrs.)	SolarIntensity(W/m2)	T_{amb} (°C)	T1(°C)	T2(°C)	T3(°C)	T4 (°C)	T5 (°C)
9:00	376	23	40.6	25.7	23.3	21.7	
9:30	460	25	64.1	29.8	25.9	25.5	
10:00	535	25	85	33.5	26.3	27.4	23.6
10:30	662	26	103.1	37	29	28.9	25.7
11:00	742	27.5	120.6	44.9	41.9	32.4	31.8
11:30	850	28.5	123.3	49.8	44.3	40.2	38.5
12:00	877	30	141.4	93.6	90.2	79.4	76.5
12:30	892	30.5	144.4	113.7	107.7	99.3	87.3
13:00	872	30.5	127.2	121.2	117.7	106.6	
13:30	843	31	118.5	119.7	116.4	111.5	
14:00	767	31	113.9	111.4	109.3	105	
14:30	712	31.5	108.4	106.6	102.3	101.7	
15:00	516	31	105.5	101.7	98.9	99.4	32.8
15:30	452	31	103.1	95.7	67.6	92.7	55.5
16:00	312	31	101.1	84.4	56.1	85.1	77.5
16:30	168	30	97.3	67.3	44.5	65.4	89.3
17:00	18	28.5	94.4	59	32.1	58	

The maximum temperature inside evacuated tube was 144.4°C at 12:30hr while at the same time temperatures at header exit, header inlet, PCM, cooking port inlet were 113.7°C, 107.7°C, 99.3°C and 87.3°C respectively as shown in Fig. 15. The maximum temperature attained by HTF inside cooker and PCM were 119.7°C and 111.5°C respectively.In the morning session cooking load was placed in the cooker at 10:00hr. Initially, the temperature of cooking load was nearly ambient temperature. As the solar intensity increases, the temperature of heat transfer fluid (transformer oil) rises and heat energy is transferred to the cooking vessel through PCM. At the same time, some part of the solar energy is stored by PCM. The food was found to be well cooked at 12:30hr and maximum temperature of food was 87.3°C.In the evening session, the gate valves were closed at 15:00hr and food was placed in the cooker and pump was OFF. In the beginning, the temperature of cooking load was nearly ambient temperature.

As the solar intensity decreases, the temperature of heat transfer fluid (transformer oil) decreases. During this time PCM transfer its stored energy to the cooking vessel. The food was well cooked at 16:30hr.

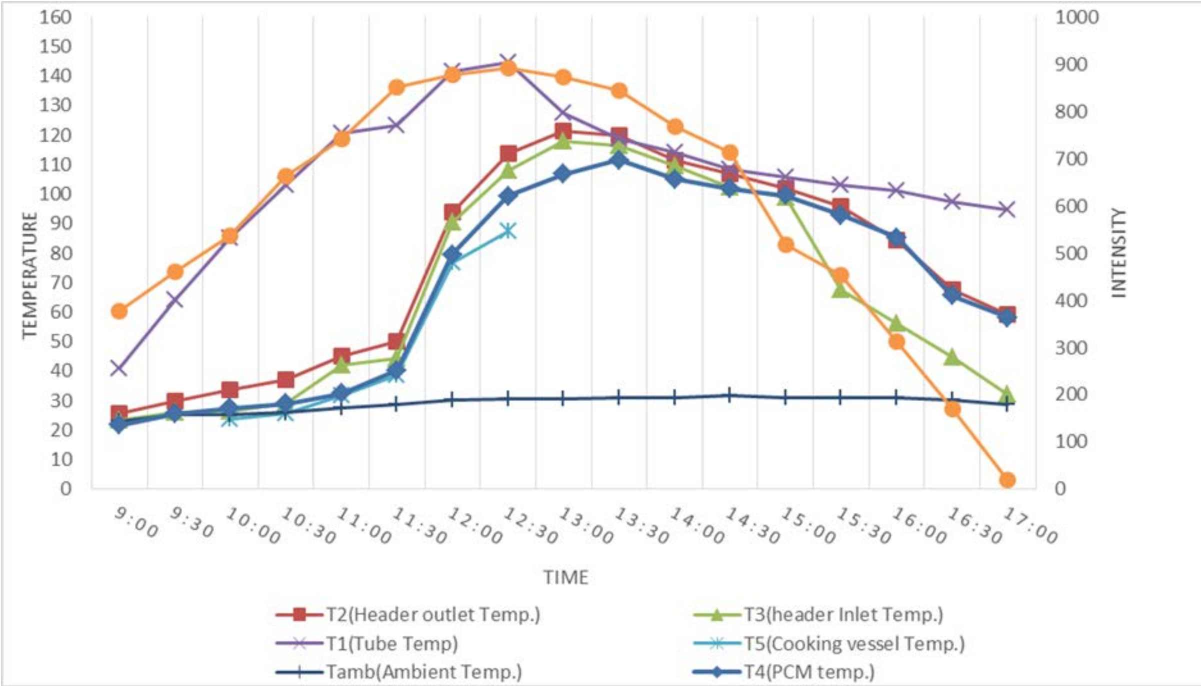

Fig.14 Variation of temperatures and solar intensity with time in case of both valves closed and transformer oil as heat transfer fluid on July 26, 2015

V. CONCLUSION

The main objective of the present research work was to explore the feasibility of solar cooker with the thermal storage unit for late evening cooking as an alternative to the cooking based on LPG gas. Major attention in this work has been given to the solar cooking based on evacuated tube collector with forced circulation of heat transfer fluid due to its advantage of working without any tracking system and to be driven by solar energy. The main conclusions from the present work are:

1. The maximum temperature of transformer oil as HTF at cooking vessel inlet was 98.4°C and inside the evacuated tube was 100.7°C for 700 ml of water as cooking load.
2. With transformer oil as HTF, the temperature of PCM at 17:00 hrs lies in the range of 79.8-84 °C when the pump is ON and when the pump is OFF the temperature lie in the range of 82.1-91.6 °C.
3. The successful cooking was carried out with transformer oil as HTF and both pump ON and OFF showed the feasibility of solar cooker based on evacuated tube collector for day time cooking as well as evening time cooking in Indian climatic conditions.
4. So overall it can be concluded that the acetanilide is the most suitable phase change material for evening cooking in Indian summer climate as stored heat is maximum. The maximum temperature of acetanilide lies in the range of 84-91°C at 17:00hr which is sufficient for evening cooking.
5. The above results show the feasibility of solar cooker with ace amide as thermal storage unit and transformer oil as a heat transfer fluid with forced circulation around the cooking vessel for late evening cooking in Indian summer climatic conditions.

VI. FUTURE WORK

The present work experimentally investigated the potential of solar cooker based on evacuated tube collector for late evening cooking. In this experimental research work, a comparison of thermal performance of solar cooker based on evacuated tube collector with two different heat transfer fluids and various phase change materials has been made. However, there are still many other issues that may be investigated. Recommended future studies are as follows:

1. To investigate the thermal performance of solar cooker for indoor cooking with acetanilide as storage unit based on evacuated tube collector for late evening cooking.
2. Experimental investigation of various methods to increase the heat transfer from working fluid to cooking vessel through PCM inside the solar cooker.
3. Experimental investigation of solar cooker based on different concentrating collectors with thermal storage unit by reducing the charging time of phase change material.

Optimization of design of solar cooker for reducing the heat losses during discharging process.

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